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A two-sided market platform analysis for the electric vehicle adoption: Firm strategies and policy design

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ABSTRACT

This study explores how to facilitate the electric vehicle (EV) diffusion from a two-sided market platform competition. We develop a stylized model depicting the platform competition between electric and gasoline vehicles by combining indirect network effects of consumer and energy supplier sides as well as vehicle manufacturers' profits. The findings of this study provide several meaningful strategic and policy implications for EV manufacturers and policymakers who wish to enhance EV diffusion. First, EV sales are significantly influenced by indirect network effects from the energy supplier side to the consumer side, and vice versa. This implies that EV manufacturers who wish to boost EV diffusion should implement a strategy providing energy suppliers with incentives to willingly join the EV platform. Second, the dynamic nature of the effects of energy costs on platform competition might render counter-intuitive evidence that the drop in oil prices does not always negatively influence EV sales. This requires EV manufacturers to prepare a contingent strategy adjusting to such unexpected conditions. Third, governments should consider the energy supplier side as well as the consumer side in designing EV diffusion policies. When governments have a very challenging EV diffusion target, a balanced policy, which treats both gasoline and electric vehicle technologies fairly, may be more effective than a consumer subsidy policy.

1. Introduction

The transportation sector accounts for 22% of the world's greenhouse gas emissions (IEA, 2012a) and is projected to consume more than 40% of fuel energy globally by 2035 (IEA, 2012b). This sector is expected to play a critical role in a transition to a low-carbon economy. In particular, electric vehicles (EVs), among other alternative green vehicles such as hybrid, fuel cell, and clean diesel cars, have been paid the most attention. EVs have several advantages over conventional gasoline-powered vehicles (GVs), including low noise and low energy cost, as well as less pollutant emissions. With these advantages and governments' EV promotion policies, the market share of EVs in the automobile industry in Europe has been predicted to surpass that of GVs by 2030 (Günther et al., 2015). As things stand, however, the actual market penetration of EVs has not been significantly fast as expected. For instance, China has set up a goal of having five million EVs on the road by 2020. The goal was met less than 1% by mid-2013 (De Neve, 2014). Many other countries have observed the same phenomenon that EV diffusion is not as fast as anticipated (Foy and Correspondent, 2014).

With the emergence of electrification of the transportation sector, researchers have explored the diffusion, adoption, and

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transition processes of EVs. Academic research, however, in this field currently faces challenges at many levels. First, a platform competition has been little addressed in exploring the diffusion of EVs (e.g. Rhee et al., 2012). The EV diffusion should engage multiple stakeholders including EV/GV manufacturers, consumers, and energy suppliers and they interplay. Consumers purchase a vehicle from manufacturers and pay to energy suppliers for charging. The availability of the station influences the utility of consumers, and the profitability of energy suppliers relies on a population of automobile consumers. Besides, vehicle consumers and energy suppliers have an option to join either EV or GV markets, and their decisions influence each other (Rhee et al., 2012). Such an interactive effect is one of the fundamental elements in a two-sided market platform market (see, e.g., Eisenmann et al., 2006). A transition from GVs to EVs can be characterized as a competition between the EV platform versus the GV platform competing to attract consumers (i.e., which vehicle to buy between a GV and an EV) as well as energy suppliers (i.e., which station to operate between a gas station or an electric charging station). The literature, however, has focused more on consumer purchase attitude including the effects of government subsidies and consumers' range anxiety on EV adoption (e.g., Langbroek et al., 2016; Lim et al., 2014). The complex and dynamic nature of an automobile industry in which two technology platforms compete have been little examined. Second, previous studies have paid little attention to indirect network effects, depicting the utility of participants in a group (e.g., consumers) depends on the number of participants in the other group (e.g., energy suppliers). The effects are believed to play a crucial role in penetration of EVs into the automobile market. In actuality, energy suppliers for the GV platform (i.e., gas stations) are dominant in the network effect, which in turn act as a big entry barrier to a new technology platform (e.g., EVs) despite EVs having several merits over the existing GV platform. Recent studies have started to consider such indirect network effects in a two-sided market of EVs (e.g., Li et al., 2016; Yu et al., 2016); however, the role of manufacturers is still neglected in the literature. Third, several previous studies have focused on examining and comparing the effects of policy options (e.g., green vehicle subsidy policies) on consumers' choice of an EV (e.g., Beresteanu and Li, 2011; Perdiguero and Jiménez, 2012). Only a few studies explore the EV manufacturer's decision making considering a competition with the GV manufacturer (e.g., Conrad, 2006; Huang et al., 2013). Furthermore, energy costs have not been incorporated into analytic models, despite that the EV adoption is believed to be significantly influenced by the prices of gasoline as well as electricity (Beresteanu and Li, 2011). Collectively, the literature has provided little practical implications for EV manufacturers' strategic decision-making.

To address this gap in the literature, this study explores a two-sided market platform competition between the extant GV and emerging EV platforms through developing a stylized model. We examine the GV and EV manufacturers' pricing decisions and government incentive policies that facilitate the EV diffusion by combining consumers' and energy suppliers' decision on which automobile platform they are likely to join. This study makes three main contributions to the field. First, it is an early effort to develop a model of platform competition in a two-sided market delineating the interactions of all players, including manufacturers, consumers, and energy suppliers. Second, this study examines the effects of energy costs on EV sales and a manufacturer's profits. Interestingly, we provide evidence that the drop in gasoline prices might not negatively influence the EV diffusion and the EV manufacturer's profits, which lead to a strategic implication for the manufacturer that curtailing production costs may be a more effective option than reducing energy costs. Third, this study provides policy implications to enhance the EV adoption under a situation in which the platform competition exists.

The remainder of this paper is organized as follows. Section 2 covers the theoretical background and Section 3 presents our research models and assumptions. Section 4 provides strategic implications for the EV manufacturer based on the model analysis. Section 5 presents an extended research model, results, and interpretation for policy implications. The last section summarizes the research results and proposes future research directions that can address the limitations of the study.

2. Theoretical background

We employed an industrial organization (IO) approach to explore competition between EV vs. GV. The EV diffusion should engage multiple stakeholders including EV/GV manufacturers, consumers, and energy suppliers and their decisions influence each other (Rhee et al., 2012). By capturing such an interactive effect, IO is appropriate to provide significant insights and implications for EV manufacturers as well as policy-makers. With this in mind, this study leverages a two-sided market and platform competition theory and adjacent research streams, such as firm strategies and government policies to promote green vehicle diffusion.

First, we utilized a concept of platforms, which are generally described as products and services that bring together groups of users in two-sided networks (Eisenmann et al., 2006) to develop a model delineating the dynamic nature of competitions between GV and EV markets. An extensive literature has explored two-sided markets and indirect network effects for various products, including the compact disc (CD) player and CD titles (Gandal et al., 2000), credit cards (Armstrong and Wright, 2007), and video games and game consoles (Clements and Ohashi, 2005; Zhou, 2016). Platform providers (e.g., manufacturers) realize that decision making on production quantity and price should be different from the conventional market because of network effects engendered from the platform (Bhargava et al., 2013). Armstrong's (2006) study, which has served as a cornerstone for other platform studies, analyzes competing platform providers' pricing decisions by considering two different conditions in which agents are forced to choose one platform and allowed to join both platforms. Rochet and Tirole (2003) classify platform competitions into the for-profit and not-for-profit cases and investigate how price and social welfare are determined in each case. Our study extends previous platform studies to a green vehicle diffusion context by incorporating direct interactions between consumers and energy suppliers as well as indirect effects. Furthermore, we extend this model to examine the effects of green vehicle diffusion policies (e.g., consumer subsidy on EV purchase) in terms of EV adoption quantity and social welfare under platform competitions.

Second, a growing number of studies have investigated firms' decision-making within the green vehicle diffusion context. Particularly, the recent literature has focused on the effects of charging infrastructure on the EV diffusion (Avci et al., 2014; Rhee et al., 2012). For instance, Lim et al. (2014) examine the effects of consumers' anxiety over the range of EVs as well as resale prices on EV diffusion. They provide evidence that such consumer anxieties and charging infrastructure (i.e., a size of battery business) co-influence EV manufacturers' pricing decisions. Avci et al. (2014) suggest a battery swapping system for promoting the EV diffusion based on their finding that consumers' EV range anxiety can be offset by the number of charging stations. Mak et al. (2013) present robust optimization models under demand uncertainty to analyze battery swapping infrastructure strategies of a charging service provider. Conrad's (2006) study also stress the effect of indirect network externalities engendered from imparity of gasoline and charging infrastructure. Based on these relevant studies, we develop a model for the EV manufacturer's strategy by incorporating the competition with a gasoline car platform, energy suppliers' decision to choose a platform to join, and bilateral interactions between the energy supplier and car consumer, as well as energy costs.

The third research stream related to our current study is about governments' green vehicle policies, which can be categorized as EV demand creation, EV infrastructure, technical standardization, and green vehicle R&D policies (Perdiguero and Jiménez, 2012). Among them, consumer subsidy policies have been most widely examined and implemented in facilitating EV diffusion. For instance, Beresteanu and Li (2011) and Gallagher and Muehlegger (2011) provide empirical evidence that government subsidies on a consumer side have a significant and positive effect on sales increase of hybrid vehicles. However, Langbroek et al. (2016) present an opposing result, indicating that a government subsidy may backfire for the consumer having a high level of environmental friendliness. Collectively, our study extends consumer subsidy policies to incorporate energy supplier side utility from the two-sided market platform perspective.

Few studies have examined the EV policies from a two-sided market perspective. The studies of Li et al. (2016) and Yu et al. (2016) have served an essential basis for exploring EV policies with the platform approach. First, Li et al. (2016) provide empirical evidence of the existence of indirect network effects in the process of green vehicle diffusion. Based on the analysis, they contend that subsidy on the energy supplier side might be more effective than that on the consumer side. Their study does not explicitly consider a firm's decision (either vehicle manufacturer or energy supplier); however, it presents a significant implication for the impact of charging infrastructure on the EV diffusion. Second, Yu et al.'s study (2016) examines a consumer subsidy policy with a two-sided market perspective. Their model depicts an EV investor's operational decision-making such as pricing and station location problem and provide evidence that EV consumers' price sensitivity might influence the energy supplier's decision, and thus differ the effectiveness of EV diffusion policies. Both studies address indirect network effects and green vehicle policies as well. Their focuses, however, are somewhat different in that way: While Li et al. (2016) emphasize the effect of charging infrastructure, Yu et al. (2016) more focus on a firm's (an EV investor's) operational decisions and the effect of consumers' preference.

Collectively, this study is one of very early and few studies to explore EV diffusion from a firm strategy and policy sides by explicitly considering indirect network effects between consumers and energy suppliers from the two competing platforms (i.e., GV and EV markets).

3. Research models

This study examines the competition between the GV and EV platforms based on Armstrong (2006)'s model (Fig. 1). We employed an industry platform concept to delineate the characteristics of our automotive technology platform model. In an industry ecosystem context, we defined a platform as a technology that serves as a foundation upon which firms can build their products. Gawer (2011) depicts an industry platform as "a building block that provides an essential function to a technological system in which a product, service or technology that is developed by one or several firms, and that serve as foundations upon which other firms can build complementary products, services or technologies." From this perspective, several firms (i.e., automotive manufacturers) in each EV/GV automotive technology platform build complementary products (i.e., automobiles) based on the automotive technology.

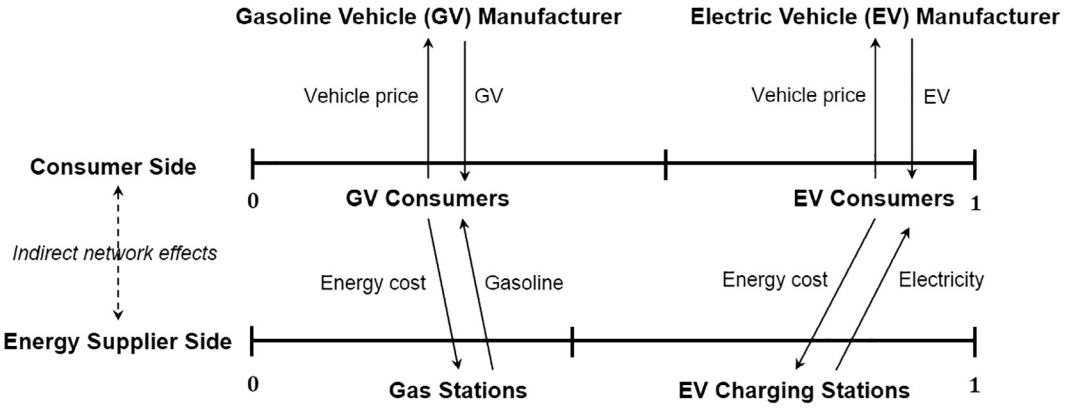


Fig. 1. A two-sided market platform competition model.

Noteworthy is that no distinct platform provider controls the technology in each of automotive technology in our model, which is different from a case where platform provider can be specified (e.g., Window and Android provided by Microsoft and Google, respectively).

The model depicts that EV and GV platforms compete each other to attract two types of agents: car consumers that decide which vehicle (between a GV and an EV) to buy, and energy suppliers that decide (or invest) which energy station (between a gasoline and a charging station) to operate (or invest in). That is, energy suppliers select one platform by joining either charging station network such as Chargepoint or gas station network such as BP. In the GV platform, the GV manufacturer sells GVs to GV consumers, and consumers pay to gas stations to buy gasoline. Likewise, the EV manufacturer sells EVs to EV consumers, and consumers pay to electric stations to charge their batteries. Note that each platform demonstrates indirect network externalities between car consumers and energy suppliers that belong to the platform, indicating that the utility of a car consumer is influenced by the number of energy suppliers and vice versa.

The platform competition is described sequentially as follows. In period 1, the GV manufacturer and EV manufacturer decide the level of their car price simultaneously.[1] In the following period, both the car consumer and energy supplier simultaneously decide which platform to join by determining which vehicle (between a GV and an EV) to buy by the consumer and which station (between a gas and a charging station) to operate by the supplier. The profits of each manufacturer are realized based on the quantity of consumers and the vehicle price.

This model presents a decision problem for each player (i.e., the manufacturer, consumer, and energy supplier) in the game and its corresponding assumptions. Noting that the game is solved by backward induction, we describe the problems of decision making in period 2 first. The problems are divided into that of the consumer and energy supplier for a given GV price p_{GV} and EV price p_{EV}. First, the consumer's decision is to choose a vehicle in order to maximize their utility. In line with Conrad (2006), we assume that consumer preference for two types of vehicles are horizontally differentiated. The size of the consumer group is normalized to 1 and uniformly distributed over [0, 1] as in Hotelling's linear city model. On the continuum over zero to one, a GV takes the zero position while an EV takes the one position. The consumer's valuation on each vehicle is heterogeneous based on its distance from the chosen vehicle. The consumer located at $x \in [0,1]$ can gain utility $u_{GV}(x)$ and $u_{EV}(x)$ for GV purchasing and EV purchasing, respectively, as follows:

$$u_{GV}(x) = u_0 - t_c x - (p_{GV} + r_{GV}) + k_c y_{GV} \tag{1}$$

$$u_{EV}(x) = u_0 - t_c(1-x) - (p_{EV} + r_{EV}) + k_c y_{EV} \tag{2}$$

Eqs. (1) and (2), representing the net utility for each vehicle choice, include three components: the benefit from car purchasing, purchasing and operating costs, and indirect network effect. First, the consumer benefit generated from a car purchasing (a GV or an EV) is determined as the same base utility u_0 minus an individual heterogeneity factor (i.e., a transportation cost). Specifically, this model depicts that the transportation cost is incurred in proportion to the distance toward each vehicle, that is, $t_c x$ and $t_c(1-x)$ for a GV and an EV, respectively, where t_c represents a transportation cost parameter. Second, purchasing and operating costs for a GV consumer include purchasing cost p_{GV} and operating cost r_{GV}, which represent the energy cost defined as mileage × (energy price/fuel efficiency). Likewise, purchasing and operating costs for an EV consumer are the summation of p_{EV} and r_{EV}. We assume that mileage is independent of vehicle type and energy price. Also, following from the empirical evidence in U.S. Department of Energy (2013), we assume that the energy cost for an EV is lower than that for a GV, as $r_{EV} < r_{GV}$.[2] Third, consumer utility is influenced by energy supply infrastructure. It increases in proportion to the number of corresponding energy suppliers with a coefficient k_c, which represents the indirect network effect from the energy supplier to the consumer. Let y_{GV} and y_{EV} be the number of gas stations and charging stations, respectively. Then, the indirect network effects to the GV consumer and EV consumer are represented as $k_c y_{GV}$ and $k_c y_{EV}$, respectively.

The decision problem of energy suppliers on which platform (between a gas station and a charging station) they are willing to join can be modeled in a similar manner. Two alternatives for the energy supplier to choose (i.e., a gas station and a charging station) are horizontally differentiated, indicating that the size of the energy supplier group is uniformly distributed over from zero (a gas station) to one (a charging station). Net utility of the energy supplier can be modeled as follows:

$$v_{GV}(y) = v_0 - t_s y + r_{GV} + k_s x_{GV} \tag{3}$$

$$v_{EV}(y) = v_0 - t_s(1-y) + r_{EV} + k_s x_{EV} \tag{4}$$

First, the utility generated from operating an energy supply station (either gas or charging station) is expressed by base utility v_0, which is identical for all suppliers, minus an individual heterogeneity factor (i.e., $t_s y$ for a GV platform participant and $t_s(1-y)$ for an EV platform participant where t_s is a transportation cost). It implies that each might have different information, expertise, and eco-friendliness, etc. for the two alternatives. Second, the energy supplier increases utility by selling energy to the consumer that belongs to the same car platform. With an assumption that energy production costs are the same as in each platform, such utility is noted as r_{GV} for the gas station operator and r_{EV} for the charging station operator. Third, the utility of energy supplier increases as the number

[1] This game can be modeled as a Stackelberg game model, assuming that a GV is the first mover as an incumbent and an EV is a follower as a new entrant. The overall results, however, are not much different.

[2] U.S. Department of Energy (2013) reports that the energy cost of running an EV remained lower than that of running a GV by analyzing the U.S. data between 2001 and 2013. They assume same driving distance and similar car model between two cars for comparison.

of corresponding vehicle consumers rises, proportionally with a coefficient k_s, representing the indirect network effect from the consumer to the energy supplier. $k_s x_{GV}$ indicates the indirect network effects upon a gas station for given x_{GV} units of GV consumers; likewise, $k_s x_{EV}$ indicates that of a charging station for given x_{EV} units of EV consumers.

Aforementioned network effect parameters and transportation cost parameters have some economic implications as follows: First, k_c and k_s measure the degree of the indirect network effect in a two-sided market. k_c (k_s) represents an utility increment of a consumer (an energy supplier) when one unit of energy supplier (car consumer) is added to the corresponding platform. This indicates that the platform choice decision (i.e., either EV or GV platform) by automobile consumers and energy suppliers highly affect each other if indirect network parameters are significant. Second, t_c and t_s, as transportation cost parameters, measure the heterogeneity of the consumer's and energy supplier (investor)'s preference on the two alternatives, respectively. For instance, a higher level of transportation cost implies an individual energy supplier's preference for a gas station vs. a charging station is highly heterogeneous each other. A low level of transportation cost indicates a homogenous preference among energy suppliers. In a situation in which preference is relatively homogeneous, a choice between the two alternatives is sensitive to changes in external factors such as energy and vehicle prices.

In the first stage of the model, the GV and EV manufacturers simultaneously decide their vehicle price with an objective function of maximizing profits. Given c_{GV} and c_{EV}, representing the unit production cost of each manufacturer, respectively, the manufacturer' problems are formulated as

$$\max_{p_{GV}} \pi_{GV}(p_{GV}, p_{EV}) = (p_{GV} - c_{GV}) x_{GV}(p_{GV}, p_{EV}) \tag{5}$$

$$\max_{p_{EV}} \pi_{EV}(p_{GV}, p_{EV}) = (p_{EV} - c_{EV}) x_{EV}(p_{GV}, p_{EV}) \tag{6}$$

where π_{GV} and π_{EV} are profit functions for the GV manufacturer and the EV manufacturer, respectively, and $x_i(p_{GV}, p_{EV})$ is the sales quantity of each vehicle as a function of two vehicle manufacturers' pricing decisions. In addition, this model assumes that the value $k_c k_s$, which indicates the degree of indirect network externalities, does not exceed a certain threshold, $t_c t_s$. This assumption prevents accrual of an exceptional case of excessive significant network externalities. In actuality, the impact of network externality in the automobile industry is very limited, when compared to that in the information and communication technology (ICT) sector. Table 1 summarizes the notations used in our models.

4. Manufacturers' pricing decision and strategic implications

In this section, we present the results of our model from the manufacturer's perspective and discuss strategic implications (Section 4.1). We then extend our model by allowing the heterogeneous indirect network effects of the consumer and discuss how it alters our main findings (Section 4.2).

4.1. Analysis for a case of homogeneous indirect network effects of the consumer

To reach the subgame perfect equilibrium, we figured out numbers of consumers and energy suppliers that join each platform as a function of the car prices, p_{GV} and p_{EV}. We first find the location $\tilde{x}$ of the consumer in the unit line [0,1] whose preference for the GV and EV are equalized such that $u_{GV}(\tilde{x}) = u_{EV}(\tilde{x})$. Note that $\tilde{x}$ not only depends on given p_{GV} and p_{EV}, but also depends on the number of energy consumers in each platform, i.e., y_{GV} and y_{EV}. Considering that the number of energy suppliers are normalized as one such that $y_{GV} + y_{EV} = 1$, we obtain this location as a function of p_{GV}, p_{EV}, and y_{GV} (Eq. (7)).

Table 1
Summary of notations.

Notation	Description
p_i	Price of i
r_i	Energy cost of i
x_i	Number of consumers buying i
y_i	Number of energy suppliers providing energy for i
π_i	Profit of a vehicle manufacturer producing i
c_i	Unit production cost of i
u_i	Net utility of a consumer buying i
v_i	Net utility of an energy supplier providing energy for i
u_0	A consumer's base utility for buying a car
v_0	An energy supplier's base utility for operating gas or charging station
k_c	Network effect from the supplier to the consumer
k_s	Network effect from the consumer to the supplier
t_c	Transportation cost for a consumer side
t_s	Transportation cost for an energy supplier side
ϵ	Policy level

Note: $i \in \{GV, EV\}$ where GV represents gasoline vehicle and EV represents electric vehicle.

$$\tilde{x}(p_{GV},p_{EV},y_{GV}) = \frac{t_c - k_c + 2yk_c - p_{GV} + p_{EV} - r_{GV} + r_{EV}}{2t_c} \tag{7}$$

Likewise, we find the location $\tilde{y}$ of the energy supplier whose preference for the gas station and charging station are equalized such that $v_{GV}(\tilde{y}) = v_{EV}(\tilde{y})$. This location, which is a function of p_{GV}, p_{EV}, and y_{GV}, is obtained in Eq. (8).

$$\tilde{y}(p_{GV},p_{EV},x_{GV}) = \frac{-k_s + t_s + 2k_s x + r_{GV} - r_{EV}}{2t_s} \tag{8}$$

The locations $\tilde{x}(p_{GV},p_{EV},y_{GV})$ and $\tilde{y}(p_{GV},p_{EV},x_{GV})$ also indicate the number of consumers that choose a GV for the given number of y_{GV} and the number of energy suppliers that decide to operate a gas station for the given x_{GV}, respectively. Hence, by solving Eqs. (7) and (8) simultaneously, we can figure out the numbers of consumers and energy suppliers that join the GV platform for given prices of the two vehicles from Eqs. (9) and (10), respectively.

$$\tilde{x}_{GV}(p_{GV},p_{EV}) = \frac{t_s t_c - k_s k_c + t_s(p_{EV} - p_{GV} - r_{GV} + r_{EV}) + k_c(r_{GV} - r_{EV})}{2(t_s t_c - k_s k_c)} \tag{9}$$

$$\tilde{y}_{GV}(p_{GV},p_{EV}) = \frac{t_s t_c - k_s k_c + t_c(r_{GV} - r_{EV}) + k_s(p_{EV} - p_{GV} - r_{GV} + r_{EV})}{2(t_s t_c - k_s k_c)} \tag{10}$$

The number of EV consumers ($\tilde{x}_{EV}$) is then $1-\tilde{x}_{GV}(p_{GV},p_{EV})$, while the number of charging station suppliers ($\tilde{y}_{EV}$) is $1-\tilde{y}_{GV}(p_{GV},p_{EV})$. Substituting these into the profit function of each manufacturer in Eqs. (5) and (6) renders optimal solutions for prices, sales quantities, and profits of two GV and EV manufacturers. Under the assumption that $k_c k_s < t_c t_s$, we can reach the unique equilibrium of the manufacturers' pricing decisions and corresponding sales quantities as well as profits as Proposition 1 delineates.

Proposition 1. *The equilibrium prices of each vehicle manufacturer $i \in \{GV,EV\}$, corresponding sales quantities, and profits are as follows:*

$$p_i^* = \frac{3(t_c t_s - k_c k_s) + (r_i - r_{-i})(k_c - t_s) + t_s(2c_i + c_{-i})}{3t_s} \tag{11}$$

$$x_i^* = \frac{1}{2} + \frac{(r_i - r_{-i})(k_c - t_s) + t_s(c_{-i} - c_i)}{6(t_c t_s - k_c k_s)} \tag{12}$$

$$\pi_i^* = \frac{(3(t_c t_s - k_c k_s) + (r_i - r_{-i})(k_c - t_s) + t_s(c_{-i} - c_i))^2}{18t_s(t_c t_s - k_c k_s)} \tag{13}$$

To examine changes in the manufacturers' equilibrium profits according to changes in energy costs, we conduct a comparative statics analysis with respect to equilibrium prices, sales quantities, and manufacturers' profits (Eqs. (11)-(13), respectively). The results lead to the following Proposition 2. We present all the necessary proofs in Appendix A.

Proposition 2. *The equilibrium prices, sales quantities, and profits of manufacturer $i \in \{GV,EV\}$ and its competitor, manufacturer $-i$ change with respect to energy cost of platform i as follows:*

(i) *If $k_c > t_s$, manufacturer i's price, sales quantity, and profits are increasing as energy cost of platform i (r_i) increases, whereas manufacturer $-i$'s price, sales quantity, and profits are decreasing.*
(ii) *If $k_c < t_s$, manufacturer i's price, sales quantity, and profits are decreasing as energy cost of platform i (r_i) increases, whereas manufacturer $-i$'s price, sales quantity, and profit are increasing.*

Interestingly, Proposition 2 implies that a decrease in energy cost (energy price) may undermine the corresponding car manufacturer's profits according to circumstances, varying by the magnitude of indirect network effect, k_c, and transportation cost, t_s. The reason behind Proposition 2(i), indicating the energy cost decrease influencing consumer utility in two mixed and conflicting ways, may be twofold. First, as expected, consumers benefit directly from energy cost reduction because their utility function includes the energy cost variable. Second, a reduction in energy costs discourages energy suppliers to join the EV platform as a charging station operator, which in turn decreases the EV consumer utility function. This is a negative consequence of the indirect network effect from the energy supplier side. Such a negative effect of energy cost on consumer utility becomes salient as transition of energy suppliers from gas stations to charging stations is easy and the indirect network effect is high. In this case, the energy cost decline curtails corresponding vehicle price p_i^* and sales quantity x_i^*, and the manufacturer's profit π_i^* accordingly. This interpretation renders an additional ground for a recent prediction that low oil prices would not necessarily hinder EV sales (Shankleman, 2015; The Economist, 2015).

If transportation cost is sufficiently high such that $t_s > k_c$, a decrease in the energy cost negatively affects the corresponding car manufacturer's profit as Proposition 2(ii) delineates. The higher level of t_s implies that the groups of EV and GV investors are entirely separated, and thus their preference for the two alternatives (i.e., EV vs. GV) are hardly reversed, as observed in practice. In this situation, the drop in oil prices has a more significant impact on an increase in the number of GV consumers (because of a lower energy cost) than a decrease in energy suppliers (because of low profitability), and thus renders a favorable outcome to the GV manufacturer. This result is very in line with the result of Beresteanu and Li's (2011)' study, providing empirical evidence that falling

oil prices lower hybrid car sales.

This analysis presents a strategic implication for the EV manufacturer. Low energy costs have been addressed as one of the most appealing advantages of EVs to consumers (Evarts, 2011). Our study, however, suggests that lowering energy costs is not always an effective development strategy for the EV manufacturer. Under a situation that t_s is sufficiently lower so that transition from a gas station to a charging station, and vice versa, is very easy, a strategy aiming to curtail production costs rather than developing a low energy cost EV (i.e., a more energy efficient EV) would be more effective in order to maximize the EV manufacturer's profitability. Lower production costs can boost EV sales by reducing vehicle prices and cost competitiveness. In actuality, EV manufacturers such as Tesla and Nissan continue to focus on how to reduce EV prices via a huge R&D investment (Bullis, 2013). Governments that wish to increase the number of EVs on the road, including China, also have increased their policy and financial support to lower EV prices (Murphy, 2014). This reasoning leads to the following lemma.

Lemma 1. *A decrease in unit production cost of the EV manufacturer increases its profits, whereas it harms the GV manufacturer's profits.*

Before ending this section, we briefly discuss expected consequence if we relax our model assumptions. First, our analytic model focuses on the effect of 'energy prices (retail prices)' rather than energy production costs on the platform competition mainly because market prices are believed to better reflect the behaviors of the consumer and energy supplier simultaneously. We, however, consider a situation in which the assumption regarding the same energy production costs is relaxed. Denote energy production costs for GV and EV by e_{GV} and e_{EV}, respectively. In the presence of such heterogeneous energy production costs, the energy supplier's utility becomes $r_{GV}-e_{GV}$ for a gas station and $r_{EV}-e_{EV}$ for a charging station, while car consumers payment term (i.e., r_{GV} by GV consumers and r_{EV} by EV consumers) remains the same. It indicates that a higher level of energy production cost is negatively related to the energy supplier's utility but does not change consumers' utility. Therefore, a production cost rise could undermine the corresponding manufacturer's vehicle sales and profits whereas benefiting the competing manufacturer. Second, this study focuses on a private (commercial) fast charging station mainly because it is relevant to address significant concerns raised by EV consumers regarding range anxiety and long charging time. We, however, recognize other types of EV charging infrastructure such as a home charging system. The results of our study might be influenced via two different ways when home charging option is also accessible to consumers. On the one hand, home charging, despite its low charging speed, can enhance consumers' preference to EVs by enlarging accessibility to charging facilities, which in turn lead to higher levels of EV deployment (*direct effect*). On the other hand, home charging option might substitute demand for commercial fast-charging stations and thus reduce energy suppliers' preference to charging station investment, which hinders EV deployment in an indirect way (*indirect effect*). Such an adverse indirect effect relies on the extent of preference of EV consumers on home charging over on charging stations.

4.2. Analysis for a case of heterogeneous indirect network effects of the consumer

Section 4.1 presents the results of the analysis with the same coefficient (k_c), indicating that the indirect network effect for EVs and GVs are equal. This section examines a situation in which such an assumption is relaxed that how relative magnitude of the indirect network coefficients affects our main findings. Denote k_{GV} and k_{EV} as an indirect network coefficient for the GV consumer and EV consumer, respectively. We derive an equilibrium of the game and examine how the main findings, sensitivity analysis regarding energy prices, would be altered if consumer side indirect network effects are heterogeneous (i.e., $k_i \neq k_{-i}$) in Lemma 2.

Lemma 2. *Assume that indirect network effects of the consumers are heterogeneous. The equilibrium prices, sales quantities, and profits of manufacturer $i \in \{GV, EV\}$ and its competitor, manufacturer $-i$ change with respect to energy cost of platform i as follows:*

i. *If $k_i > 2t_S - k_{-i}$, manufacturer i's price, sales quantity, and profit are increasing in the energy price of the platform i (r_i), whereas manufacturer $-i$'s price, sales quantity, and profits are decreasing.*
ii. *If $k_i < 2t_S - k_{-i}$, manufacturer i's price, sales quantity, and profit are decreasing in energy cost of platform i (r_i), whereas manufacturer $-i$'s price, sales quantity, and profits are increasing.*

Lemma 2 shows that if the indirect network coefficient of one platform k_i is higher (lower) than the other k_{-i}, it is more likely to happen the first (second) case of the lemma. That is, an increase in energy price of one platform r_i is more likely to increase (decrease) the number of the consumers and profits of the manufacturer belonging to the corresponding platform. Strictly speaking, an increase (decrease) in the indirect network coefficient of platform i leads to $\frac{dx_i^*}{dr_i} > 0$ and $\frac{d\pi_i^*}{dr_i} > 0$ $\left(\frac{dx_i^*}{dr_i} < 0 \text{ and } \frac{d\pi_i^*}{dr_i} < 0\right)$ in a broad range of parameters.

This generalized model, allowing asymmetric indirect network coefficients between the platforms such that $k_{GV} \neq k_{EV}$, provides some implications for the EV and GV industries. Recall that k_{EV} represents an increment in the EV consumer utility as one unit of a charging station is added. EV consumers usually raise issues of range anxiety due to the limited driving range of EV (Lim et al., 2014). The development of EV technologies that extend the driving range would relieve such range anxiety and thus impact of charging infra on EV consumer's utility would lessen (i.e., k_{EV} decreases). Then, a drop in oil price would facilitate the diffusion of EV but negatively influences GV, according to the result of the analysis. Overall, while the main findings of our first analysis continue to hold, an increase in corresponding platform's coefficient widens the range of parameters for the case of Proposition 2(i).

5. Electric vehicle diffusion policies and implications

As Proposition 2 gives a hint, lowering transportation cost between a gas station and a charging station may play a crucial role in facilitating EV diffusion. In this section, we propose a policy that promotes such a transition. This policy, dubbed as a *balanced policy*, focuses on reducing energy suppliers' disutility and providing them with useful information about how to establish an energy station. Given the current complicated regulations and procedures impeding to open a new energy station (Rothenstein et al., 2011; U.S. Department of Energy, 2012), deregulation is a significant part of the policy. The balanced policy, contrary to conventional policies favoring the EV platform based on subsidies to EV consumers, treats two GV and EV platforms fairly. The literature has provided evidence that such a balanced policy is effective in reducing transition cost of the consumer choice between two competing alternatives (e.g., Aghion and Schankerman, 2000; Meagher and Ghosh, 2004).

We compare the effect of the balanced policy to that of a conventional EV subsidy-based policy in terms of the quantity of EV adoption, which has been most widely used as governments' policy target in promoting green cars (Cohen et al., 2016). Noteworthy is that we did not apparently consider the environmental externalities (i.e., ecological benefit to the society) in our analytic model for a reason. We believe that a level of EV diffusion (x_{EV}) as a performance measure can be a proxy for the ecological benefit of EV because it is in proportional to the number of EVs. Our approach is very consistent with that previous study has employed (e.g., Bernardo et al., 2016; Yu et al., 2016). Here, the vehicle production costs are assumed as zero in order to focus on examining impacts of energy costs on policy effectiveness (i.e., $c_{GV} = c_{EV} = 0$); however, implications from the results are still in effect in the non-zero production cost case.

5.1. Analysis of two alternative EV policies

Firstly, the balanced policy was examined. Under this policy, the transportation cost on the energy supplier side is lowered from t_s to $t_s - \epsilon_1$. The quantity of adopted EVs, denoted by $x^B_{EV}(\epsilon_1)$, is then represented as

$$x^B_{EV}(\epsilon_1) = \frac{1}{2} + \frac{(r_{EV} - r_{GV})(k_c - (t_s - \epsilon_1))}{6(t_c(t_s - \epsilon_1) - k_c k_s)} \tag{14}$$

With Eq. (14), the conditions in which this balanced policy is effective for EV adoption are described as follows:

Proposition 3. *Under the balanced policy, if $t_c < k_s$, a decrease in the energy supplier's transportation cost (ts) stimulates sales of EV (i.e., EV adoption). Also, the effect of transportation cost reduction on EV sales increases as the energy cost differential, $r_{GV} - r_{EV}$, increases. Otherwise, if $t_c < k_s$, the transportation cost reduction is detrimental to EV sales.*

Proposition 3 provides some meaningful implications. First, it shows that the balanced policy, treating two platforms fairly, can enhance EV adoption if the transportation cost (t_c) indicating the difference of the consumer preference between two alternatives, a GV and an EV, is low enough. This result implies that a difference in energy costs of the consumer between a GV and an EV may play a crucial role in determining the effectiveness of the policy. Second, lower energy costs of EVs (i.e., $r_{EV} < r_{GV}$) have mixed and contrasting effects on the utility of the EV energy supplier. On one side, they intensify the utility of the EV consumer, which in turn increases a positive indirect network effect from the consumer side to the energy supplier side, and eventually lead to a greater utility of the energy supplier (i.e., a charging station operator). On the other side, they undermine the utility of a charging station operator by lessening energy-selling margins. Collectively, these two conflicting effects render different effects of the balanced policy based on a lower t_s, depending on a relative size of the consumer side transportation cost (t_c) and the indirect network effect (k_s). A sufficiently low t_c outweighing the negative effect attracts consumers to join the EV platform, which in turn makes the balanced policy effective. Third, it is noteworthy that a difference in energy costs between the GV and EV platforms indicates an asymmetry between the two platforms. We can reach a conclusion that the greater such an asymmetry is, the more effective the balanced policy is.

Next, we examine a consumer subsidy policy. A subsidy to EV purchase, ϵ_2, lowers vehicle price to $p_{EV} - \epsilon_2$. The number of consumers who buy an EV at the subsidy level ϵ_2, denoted by $x^S_{EV}(\epsilon_2)$, can be obtained by substituting $p_{EV} - \epsilon_2$ for p_{EV} in Eq. (15).

$$x^S_{EV}(\epsilon_2) = \frac{1}{2} + \frac{t_s\,\epsilon_2 + (r_{EV} - r_{GV})(k_c - t_s)}{6(t_c t_s - k_c k_s)} \tag{15}$$

The result is quite intuitive, indicating that a greater consumer subsidy accordingly elevates EV sales (or adoption).

5.2. Policies comparison

We compare the effect of two EV policies, the balanced policy and consumer subsidy policy, in terms of EV sales (or EV adoption quantity). The two policies are assumed to implement up to the ϵ_1 and ϵ_2 levels, respectively, implying that the transportation cost for the energy supplier is lowered by ϵ_1 and the consumer subsidy is ϵ_2. Let us call them policy level.[3]

First, we conduct an analysis under the restricted condition of '$\epsilon_1 = \epsilon_2$'. We set the upper limit of the policy level to ensure the positive profits of the two GV and EV manufacturers so that they do not exit the market. Under the consumer subsidy policy, the condition $\pi^S_{GV}(\epsilon) \geqslant 0$ should be met. By rearranging the constraint with respect to ϵ, we obtain

[3] Policy intensity can be used interchangeably.

$$\epsilon \leqslant \frac{3(t_c t_s - k_c k_s) + (r_{EV} - r_{GV})(t_s - k_c)}{t_s} \ (\equiv M_S) \tag{16}$$

Similarly, we impose the constraint $\pi^B_{GV}(\epsilon) \geqslant 0$ on the balanced policy. With the other constraint condition $t_c t_s(\epsilon) - k_c k_s > 0$ for ϵ in Section 3, rearranging such constraints with respect to ϵ yields

$$\epsilon \leqslant \min\left\{\frac{3(t_c t_s - k_c k_s) + (r_{EV} - r_{GV})(t_s - k_c)}{r_{EV} - r_{GV} + 3t_c}, \frac{t_c t_s - k_c k_s}{t_c}\right\} \ (\equiv M_B) \tag{17}$$

Then, the range of policy levels that satisfies (16) and (17) can be presented as $\epsilon \leqslant \min\{M_S, M_B\}$. Denote $\min\{M_S, M_B\}$ by M that indicates the upper bound of the policy level. Under the constraint $\epsilon_1 = \epsilon_2$, the effectiveness of the two policies differs depending on the relative size of k_s and t_c as follows. First, in case of $k_s < t_c$, the balanced policy decreases EV sales, implying that the consumer subsidy policy is superior to the balanced policy. Second, under the condition of $k_s > t_c$, both policies enhance EV adoption. We figure out a point ϵ^o where EV sales quantities under the two policies become equal. By solving $x^B_{EV}(\epsilon) = x^S_{EV}(\epsilon)$ with respect to ϵ, we obtain the unique ϵ^o as

$$\epsilon^o = \frac{t_s(t_c t_s - k_c k_s) + k_c(t_c - k_s)(r_{GV} - r_{EV})}{t_c t_s} \tag{18}$$

With this threshold, EV sales quantities under the two policies differ as follows:

Proposition 4. *Assume that $k_s > t_c$. Comparison of EV adoption between the two policies with respect to policy level $\varepsilon \in (0, M)$ yields,*

(i) $\epsilon^o < 0$: *For all ϵ we consider, $x^S_{EV}(\epsilon) < x^B_{EV}(\epsilon)$ holds.*
(ii) $0 < \epsilon^o < M$: $x^B_{EV}(\epsilon) < x^S_{EV}(\epsilon)$ *for $\epsilon < \epsilon^o$, and $x^B_{EV}(\epsilon) > x^S_{EV}(\epsilon)$ for $\epsilon > \epsilon^o$.*
(iii) $M < \epsilon^o$: *For all ϵ we consider, $x^B_{EV}(\epsilon) < x^S_{EV}(\epsilon)$ holds.*

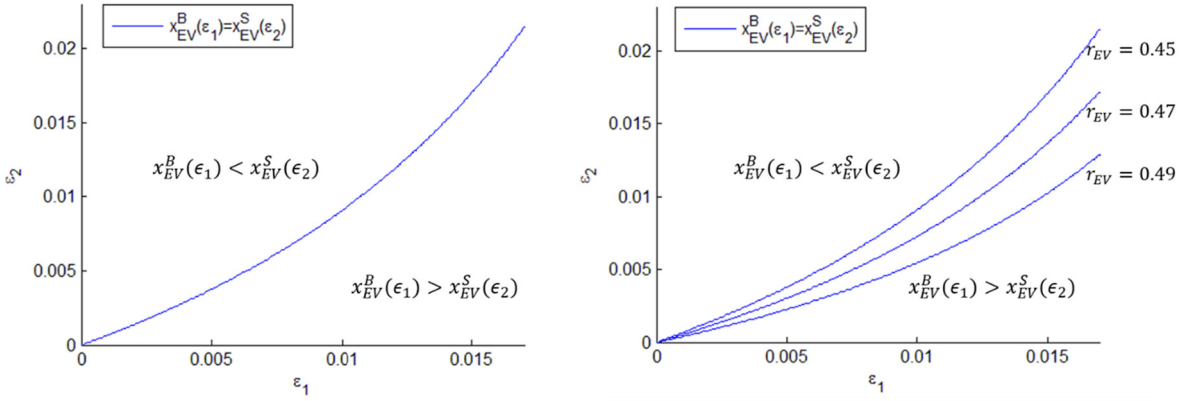
Proposition 4(i) describes a situation in which a negative subsidy (i.e., tax) is imposed on an EV or the transportation cost increases. Imposing taxes on EV purchase, however, is not realistic. Under the excessive strong policy such that $\epsilon^o > M$ as in Proposition 4(iii), GVs are expelled from the market, which is also unlikely in practice.

The second case, i.e., $0 < \epsilon^o < M$, well reflects a reality. The result indicates that the balanced policy outperforms the consumer subsidy policy only when policy level ϵ is high enough. A marginal effect of transportation cost reduction on EV sales is varying, while that of consumer subsidy is constant (Eq. (15)). Platform competition is intensified with lower transportation cost and thus its marginal impact on $x_{EV}(\epsilon)$ increases with a higher ϵ. This implies that governments having ambitious and challenging goals of the EV diffusion should execute the balanced policy rather than the conventional consumer subsidy policy.

This proposition also reveals that ϵ^o, at which the effectiveness of the two policies becomes equal, lowers as the energy cost differential $(r_{GV} - r_{EV})$ increases. Accordingly, a range of (ϵ^o, M), in which the balanced policy is preferable, widens. This implies that the balanced policy might be a more effective option in the context that the energy cost of an EV is much lower than that of a GV.

We now generalize this comparison by easing the constraint condition of $\epsilon_1 = \epsilon_2$ to be free to choose independently. Transportation cost is lowered to ϵ_1 and the subsidy level is given as ϵ_2. To explore a range in which the balanced policy is more effective than the subsidy policy, we compare the two policies in a numerical way. We set the following parameters for this numerical analysis: $k_C = 0.05$, $k_s = 0.15$, $t_c = 0.1$, $t_s = 0.11$, $r_{GV} = 0.55$, and $r_{EV} = 0.45$.

The solid line in Fig. 2(a) shows the subsidy level ϵ_2 to attain $x^S_{EV}(\epsilon_2)$, which is equal to $x^B_{EV}(\epsilon_1)$, the adoption quantity for given



(a) $r_{EV} = 0.45$ (b) $r_{EV} = \{0.45, 0.47, 0.49\}$

Fig. 2. Numerical comparisons of the EV adoption levels between the two policies for given policy levels ϵ_1 and ϵ_2.

transportation cost reduction level ϵ_1. The balanced policy is more effective in the area below the line, whereas the consumer subsidy policy is preferred above the line. Note that the graph is convex, confirming evidence that the balanced policy much outperforms as the government's EV diffusion target rises. The ratio of subsidy level (ϵ_2) to transportation cost reduction level (ϵ_1) increases to achieve the same EV adoption target. By combining with the fact that the EV adoption level $x_{EV}^{B}(\epsilon_1)$ ($=(x_{EV}^{S}(\epsilon_2))$ increases with a greater ϵ_1 level on the line, we can reach a conclusion that a more challenging (higher) EV adoption target enhances the merits of the balanced policy.

Fig. 2(b), shows changes in the threshold satisfying $x_{EV}^{B}(\epsilon_1) = x_{EV}^{S}(\epsilon_2)$ with respect to the energy cost of the EV platform. This indifference threshold curve moves upward as EV energy cost (r_{EV}) decreases. Accordingly, the area in which the balanced policy is preferred broadens, implying that the balanced policy may be more favored over the consumer subsidy policy as the gap between energy costs of the two platforms is widening. This result is very consistent with the result under a restricted condition $\epsilon_1 = \epsilon_2$ (see Proposition 4).

In addition, we compare the effectiveness of the two policies in terms of social welfare. We test that a preferred policy may differ when a policy objective changes (i.e., EV adoption versus social welfare). Social welfare is defined here as the sum of the surplus of all platform participants such as consumers and energy suppliers and the profits of manufacturers (see Appendix B for details). Denote SW^S and SW^B as social welfare under the subsidy policy and balanced policy, respectively. We employ a numerical analysis using the same parameter values.

The solid line in Fig. 3 represents the policy level pairs (ϵ_1,ϵ_2) equalizing the social welfare under the balanced policy $SW^B(\epsilon_1)$ and that under the consumer subsidy policy $SW^S(\epsilon_2)$. Below the line is the area where the balanced policy brings higher social welfare, whereas the area above the line indicates that consumer subsidy policy yields higher social welfare. The dotted line represents the threshold where EV adoption quantities under the two policies are equalized, which is the same as the threshold in Fig. 2. The results present that preferred policies slightly change depending on the purposes of the policy, and EV diffusion versus social welfare. Areas, in which a policy is more effective, are divided into four areas by combining the dotted line (the threshold under the EV diffusion purpose of government's policy) and the solid line (that under the social welfare purpose of government's policy). Table 2 summarizes scenarios that depict which policy (between the balanced and consumer subsidy) is preferred and when. The effectiveness of the two policies is influenced by the purpose of polices only in areas B and C.

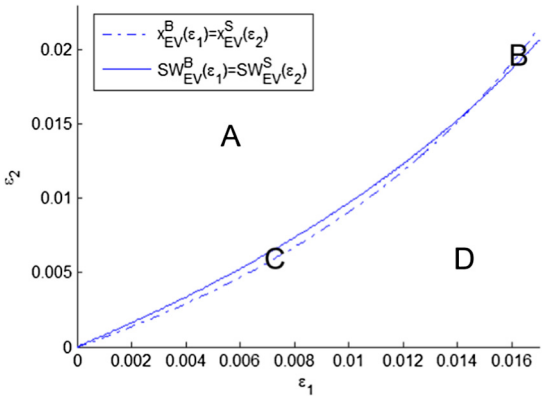


Fig. 3. Numerical comparisons of the two policies regarding social welfare.

Table 2
An effective policy with the purposes of policies.

	Purpose of policy	
Area	Social welfare	EV diffusion
A	Consumer subsidy	Consumer subsidy
B	Consumer subsidy	Balanced
C	Balanced	Consumer subsidy
D	Balanced	Balanced

6. Conclusion

This study explores the platform competition between electric and gasoline vehicles by combining indirect network effects of consumer and supplier sides as well as manufacturers' profits structure. This study has two main parts aiming to provide implications for business practitioners and policy-makers. In the first part, the equilibrium of the game is derived and the role of energy cost is investigated to generate insight for EV manufacturers. This serves as a basis for the second part of the study to explore the effectiveness of EV diffusion policies considering the reaction from the industry.

The findings of the study provide significant implications for business practitioners and policymakers who wish to facilitate electric vehicle (EV) diffusion. First, the automobile sector, characterized as platform competition, is significantly influenced by indirect network effects from the supplier side to the consumer side, and vice versa. Vehicle manufacturers should consider such network effects in developing strategies to enter a new vehicle market (e.g., EV market). In particular, such indirect effects engendered by the size of energy suppliers (i.e., charging stations) profoundly influence consumers' EV purchasing decision. EV manufacturers need to provide energy suppliers with incentives to join the EV platform. For instance, Tesla has disclosed its patents for free (Solomon, 2014), including charging infrastructure-related technologies (e.g., a high-speed battery charging technology), which is exemplary endeavor to attract more investments in EV energy infrastructure. Second, EV manufacturers should understand the dynamic nature of the effects of energy costs on platform competition between GVs and EVs. Furthermore, a relative level of indirect network effect and transportation cost that measures the individual heterogeneity for the two alternatives play as moderating roles in the relationships between energy costs and EV sales as well as manufacturers' profits. The results provide counter-intuitive evidence that the drop in oil prices does not always negatively influence EV sales, which demands the EV manufacturer to develop a contingent strategy adjusting to different conditions. For example, in a particular situation, lowering EV prices through production cost reduction may be a more effective strategy than appealing to consumers with the merit of low energy costs of an EV. Third, the results of this study present a transportation policy implication for facilitating EV diffusion. Governments should consider energy supplier side beyond mere consumer subsidy approach. The balanced policy, which treats both vehicle technologies of GVs and EVs in a fair manner, might be a better policy alternative over the consumer subsidy policy if governments set a quite ambitious and challenging goal of having much more EVs on the road. The merits of this policy also stand out when oil prices rise. Besides, policymakers should realize that the preferred plan might be changed depending on the purpose of policies (EV diffusion versus social welfare).

While this study makes several contributions to the literature by providing insights into platform competition between electric and gasoline vehicles, it still has some limitations. Future research is encouraged to address such issues as follows. First, this study does not incorporate a role of component suppliers in EV diffusion. As noted in Rhee et al. (2012), the EV requires new critical components such as batteries, and therefore incentives to parts and/or component suppliers to willingly join the EV platform should be considered in developing strategies and policies for EV diffusion. Second, this study employed a linear utility model assuming that the utility of consumer and energy supplier consists of a direct sum of the energy cost and indirect network effect, etc. Further studies would be encouraged to utilize a more complicated utility model to check generalizability of the results of this study. Besides, the energy supplier's utility needs to be elaborated to increase reality such as $v_{GV} = v_0 - t_s(1-y) + \eta \cdot r_{GV} x_{GV}$ and $v_{EV} = v_0 - t_s(1-y) + \eta \cdot r_{EV} x_{EV}$, which might be a more direct way of modeling the profits of the energy supplier. Third, from an empirical point of view, this study did not consider one-to-one mapping of the differentiated preference of consumers and energy suppliers to real data. Future research awaits attempts to link the transportation cost and empirical evidence. Besides, empirical studies on the relationship between energy price and charging/gas station deployment are needed. Fourth, given a gap in the literature that has little reported on the diffusion of EV from a platform competition perspective, we limited our attention to a competition between GV and EV. However, a multi-market competition including a more diverse range of options (e.g., HEV and PHEV) would be worthy of exploring. Future research should extend our model to incorporate other technology options such as a hybrid vehicle. Fifth, in this study, we considered a limited scope of the consumer's base utility representing the collective satisfaction of the consumer. A diverse range of factors, however, influences consumers' choice of EVs, such as driving experience, vehicle brands, environmental awareness of consumers, and eco-friendly traits of vehicles. Future research should consider how such factors interplay in affecting the heterogeneity of consumers' preference and utility.

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Appendix A. Proofs

A.1. Proof of Proposition 2

Both $x_i^*(r_i)$ and $p_i^*(r_i)$ decrease in r_i in case $k_c < t_s$. Thus, π_i^* increases as r_i decreases for the case $k_c < t_s$. In a similar way, it can be shown that π_i^* decreases as r_i decreases for the case of $k_c > t_s$. The impact of r_i on competitor's profits is determined in the opposite direction.

A.2. Proof of Proposition 3

To increase the number of EV consumers under the balanced policy, $x_{EV}^{B}(t_s)$ should decrease in t_s. Since we assume $r_{GV} > r_{EV}$, $\frac{dx_{EV}^{B}(t_s)}{dt_s} = \frac{(r_{EV}-r_{GV})k_c(k_s-t_c)}{6(t_s t_c - k_s k_c)^2} > 0$ holds if $k_s < t_c$. Otherwise, $\frac{dx_{EV}^{B}(t_s)}{dt_s} < 0$ holds.

A.3. Proof of Proposition 4

For given policy level ϵ, the point where the balanced policy and the consumer subsidy policy yield the same number of consumers is obtained as $\epsilon^o \left(=\frac{t_c(t_s^2+(-r_{EV}+r_{GV})k_c)+(r_{EV}-r_{GV}-t_s)k_c k_s}{t_c t_s}\right)$ and 0. Under the consumer subsidy policy, the number of consumers to buy an EV $x_{EV}^{S}(\epsilon)$ is linearly proportional to ϵ. Moreover, $x_{EV}^{B}(\epsilon)$, the number of consumers to choose an EV under the balanced policy, increases in ϵ and its first and second derivatives are positive. Thus, if $\epsilon^o < 0$, for all $\epsilon > 0$, it renders a result that $x_{EV}^{S}(\epsilon) < x_{EV}^{B}(\epsilon)$. In case $\epsilon^o > 0$, if $\epsilon < \epsilon^o$, then $x_{EV}^{B}(\epsilon) < x_{EV}^{S}(\epsilon)$ holds and if $\epsilon > \epsilon^o$, $x_{EV}^{B}(\epsilon) > x_{EV}^{S}(\epsilon)$ holds. With the constraint $\epsilon^o < M$, we need to consider the case $\epsilon^o < M$ and case $M < \epsilon^o$ separately. When $\epsilon^o < M$, $x_{EV}^{B}(\epsilon) < x_{EV}^{S}(\epsilon)$ for $\epsilon < \epsilon^o$ and $x_{EV}^{S}(\epsilon) < x_{EV}^{B}(\epsilon)$ for $\epsilon^o < \epsilon < M$ holds. When $\epsilon^o > M$, $x_{EV}^{B}(\epsilon) < x_{EV}^{S}(\epsilon)$ holds.

Appendix B. Definitions of social welfare and its calculation

For given policy level ϵ, social welfare (SW) is defined as the sum of each platform participants' and manufacturers' surplus. Specifically, the welfare of platform participants denoted by CS is defined as the sum of surplus of consumers (CS_C) and that of energy suppliers (CS_S). Note that the equilibrium point (i.e., two manufacturers' equilibrium prices and corresponding market share for each platform participant) changes depending on ϵ. Thus, each platform participant's perceived network effect changes, and consumer welfare changes accordingly. At the equilibrium, each platform participant's welfare can be calculated as follows:

$$CS_C(\epsilon) = \int_0^{x_{GV}^*(\epsilon)} u_{GV}(t_s(\epsilon), p_{GV}^*(\epsilon), x_{GV}^*(\epsilon), y_{GV}^*(\epsilon))dt_c + \int_{x_{GV}^*(\epsilon)}^1 u_{EV}(t_s(\epsilon), p_{EV}^*(\epsilon), x_{EV}^*(\epsilon), y_{EV}^*(\epsilon))dt_c$$

$$CS_S(\epsilon) = \int_0^{y_{GV}^*(\epsilon)} v_{GV}(t_s(\epsilon), p_{GV}^*(\epsilon), x_{GV}^*(\epsilon), y_{GV}^*(\epsilon))dt_s + \int_{y_{GV}^*(\epsilon)}^1 v_{EV}(t_s(\epsilon), p_{EV}^*(\epsilon), x_{EV}^*(\epsilon), y_{EV}^*(\epsilon))dt_s$$

The sum of two vehicle manufacturers' profits denoted by $\Pi(\epsilon)$ is obtained as follows:

$$\Pi(\epsilon) = \pi_{EV}(t_s(\epsilon), p_{EV}^*(\epsilon), x_{EV}^*(\epsilon), y_{EV}^*(\epsilon)) + \pi_{GV}(t_s(\epsilon), p_{GV}^*(\epsilon), x_{GV}^*(\epsilon), y_{GV}^*(\epsilon))$$

Finally, we obtain $SW(\epsilon) = \Pi(\epsilon) + CS(\epsilon)$.

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